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**13.9 GHZ SHORT PULSE RADAR NOISE
FIGURE MEASUREMENTS UTILIZING
SILICON AND GALLIUM-ARSENIDE
MIXER DIODES**

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**— GODDARD SPACE FLIGHT CENTER —
GREENBELT, MARYLAND**



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July 1977

**GODDARD SPACE FLIGHT CENTER
Greenbelt, Maryland**

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FIGURE MEASUREMENTS UTILIZING SILICON
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ABSTRACT

An analysis was made on two low noise Schottky barrier mixer diodes which were intended to be used in the GSFC 13.9 short pulse radar employed in sea state studies. Considered in this comparison were commercially available silicon and gallium-arsenide Schottky barrier diodes. These diodes were selected because of their particularly low noise figure in the frequency range of interest. The manufacturer's specified noise figure for the silicon and gallium-arsenide diodes were 6.3 dB and 5.3 dB respectively when functioning as mixers in the 13.6 GHz region with optimum local oscillator drive.

13.9 GHZ SHORT PULSE RADAR NOISE FIGURE MEASUREMENTS UTILIZING SILICON AND GALLIUM-ARSENIDE MIXER DIODES

INTRODUCTION

A novel test procedure was developed which characterized the responses expected by the "twice-power" and "Y-factor" methods of noise figure measurements.

This analysis was also directed at obtaining a bench mark for the receiver front end, mixer/preamplifier section, of the radar sensor. In addition, the long term objective would be to interchange detectors and examine sea state return data for improvements in the small signal response.

The test conducted on these semiconductors consisted of a modified version of the "twice-power" method for manual noise figure measurement, pulsing of the noise source.

Before continuing with the test procedure it is first necessary to define what is meant by the system noise figure. By stating a system's noise figure one can say that a measure of the sensitivity of that system is known. For as the noise figure of a system improves, approaches 0 dB, there is an associated decrease in the signal power necessary for a similar detected voltage - increased sensitivity.

System noise is essentially generated by two sources, Johnson noise and shot noise. Johnson noise is introduced into a system by the fluctuations of voltage developed across a device's junction caused by random thermal motion. Shot noise, on the other hand, is brought about by the random current fluctuations.

In a measuring system such as a detector, involving small power levels, it may be defined that the minimum detectable power is that value resulting in a signal power output from the detector equal to that of the noise. Diode noise current, either Johnson noise or shot noise, limits the effectiveness of the mixing operation by increasing the effective noise floor.

When calculating the noise power delivered by a load resistor into a system, it is convenient to assume that no mismatches occur. If this is assumed, then the noise power can be expressed as a function of a resistance, R , at temperature T , inducing a voltage V . Since noise power is of interest and not necessarily voltage

for this matched load, the available noise power can be expressed as $P' = KTB$ where K is Boltzmann's constant (1.37×10^{-23} joules/ $^{\circ}K$), T is the temperature in degrees Kelvin and B is the bandwidth of the measuring system. In actuality the available noise power level may be lower due to mismatches and losses. For these calculations losses will not be considered.

Calculating the noise power level as seen by the radar front end with a bandwidth of 200 MHz, the IF amplifier bandwidth, and at a temperature of 290 $^{\circ}K$ we obtain

$$P_1 = (1.37 \times 10^{-23} \text{ joules}/^{\circ}K) (290^{\circ}K) (200 \text{ MHz})$$

$$= 7.946 \times 10^{-13} \text{ watts.}$$

Converting watts to dBm

$$P_{1 \text{ dBw}} = 10 \log P_1 = -121 \text{ dBw}$$

or

$$P_{1 \text{ dBm}} = P_{1 \text{ dBw}} - 30 \text{ dB} = -91 \text{ dBm.}$$

This is the bandwidth limited noise power level of the matched terminating resistance.

To develop a figure of merit for the radar front end, a ratio must be developed between the actual output noise power to this theoretical minimum, -91 dBm. This figure of merit is referred to as the system noise figure, NF. Therefore,

$$NF = P_1 / KTBG$$

where G is the gain added to the system.

If a broadband noise source is introduced at the input of the device under test, (in place of the termination,) a differential power measurement at the system's output would indicate the gain bandwidth product of the device. By using a gas discharge tube as an external noise source at the input port, a noise power level, P_2 , higher than that found at room temperature is obtained. For an argon gas noise tube the effective temperature, T_2 , is about 10^4 $^{\circ}K$. By comparing the noise power levels at these two temperatures, it is possible to calculate the noise figure of the mixer.

The ratio of these two power levels, P_1 and P_2 , is calculated as follows:

$$\frac{P_2}{P_1} = \frac{(NF) T_1 + (T_2 - T_1)}{(NF) T_1}$$

By reducing and solving for NF we obtain

$$NF = \frac{(T_2 - T_1)}{T_1} \cdot \frac{1}{\left(\frac{P_2}{P_1} - 1\right)}$$

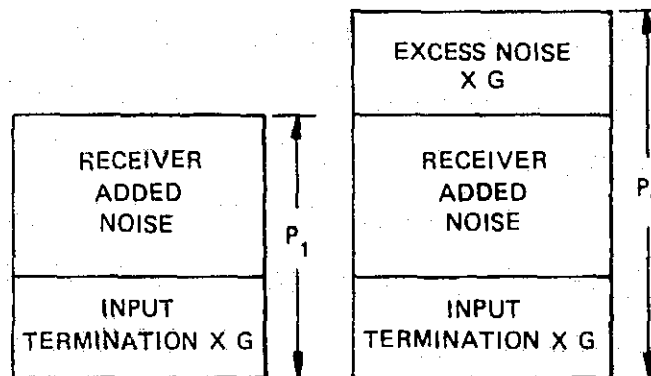
or in dB

$$NF_{dB} = 10 \log \left(\frac{T_2 - T_1}{T_1} \right) - 10 \log \left(\frac{P_2}{P_1} - 1 \right)$$

The first term on the right-hand side is a measure of the relative/excess noise power available from the argon noise source. For these calculations, this term is referred to as the excess noise ratio and is equal to 15.25 dB. /Therefore,

$$NF_{dB} = 15.25 \text{ dB} - 10 \log \left(\frac{P_2}{P_1} - 1 \right) \text{ equation 1}$$

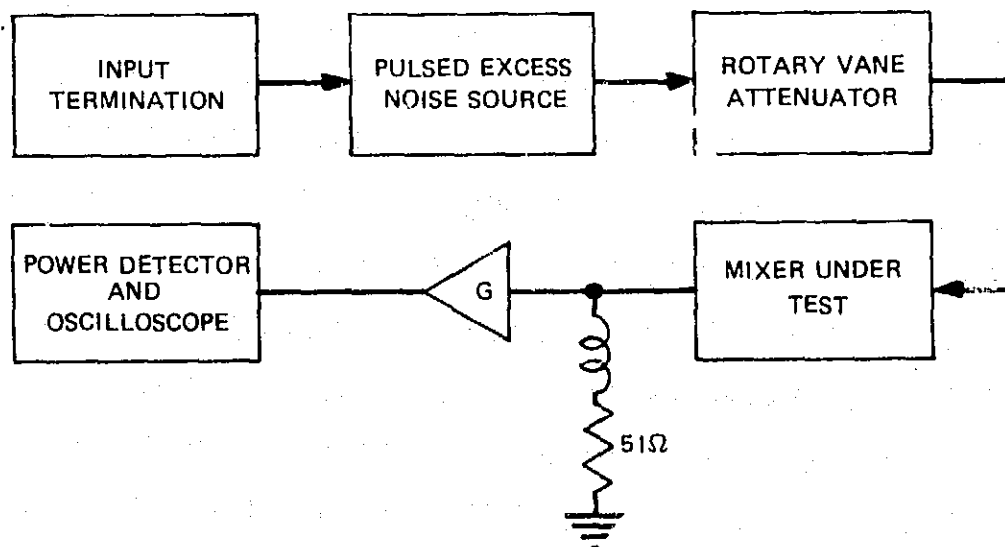
This process is illustrated below:



This method employed for making the radar front end noise figure measurement was a modification of the "twice-power" method. The test consisted of measuring P_1 and P_2 , thereby satisfying equation 1. However, the power level P would be selected such that it was twice the level of P_1 . Thereby reducing equation 1 to

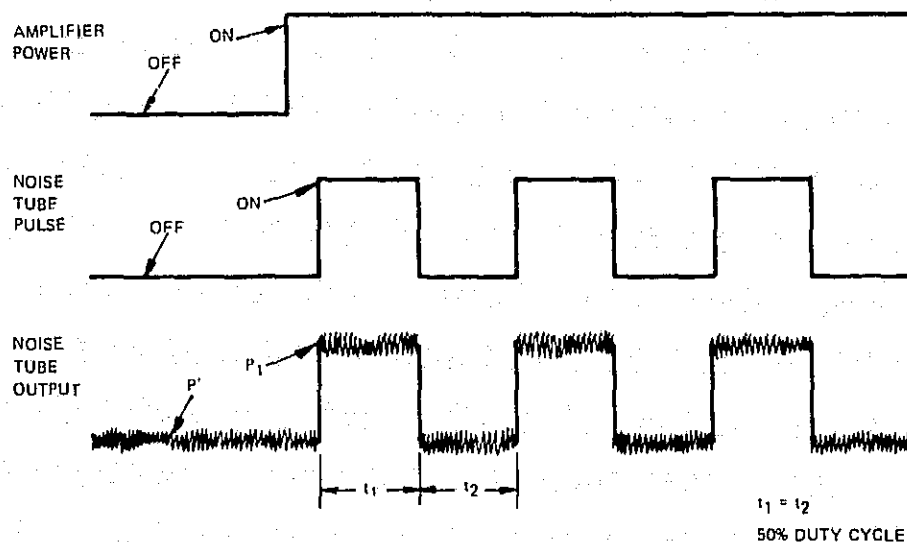
$$NF_{dB} = 15.25 - 10 \log(1) = 15.25$$

Attenuation is necessary to satisfy this condition and develop a value for the noise figure. By using the test set-up shown below, the rotary vane attenuator will reduce the excess noise source power level, detected and viewed on an oscilloscope, by 3 dB – half power. This particular arrangement is unique in that the noise tube is pulsed on and off at 50% duty cycle. This gives rise to the 3 dB or half power requirement necessary for $2P_1 = P_2$.



The Modified Method of Manual Noise Figure Measurement.

The timing waveforms for the test are shown below:

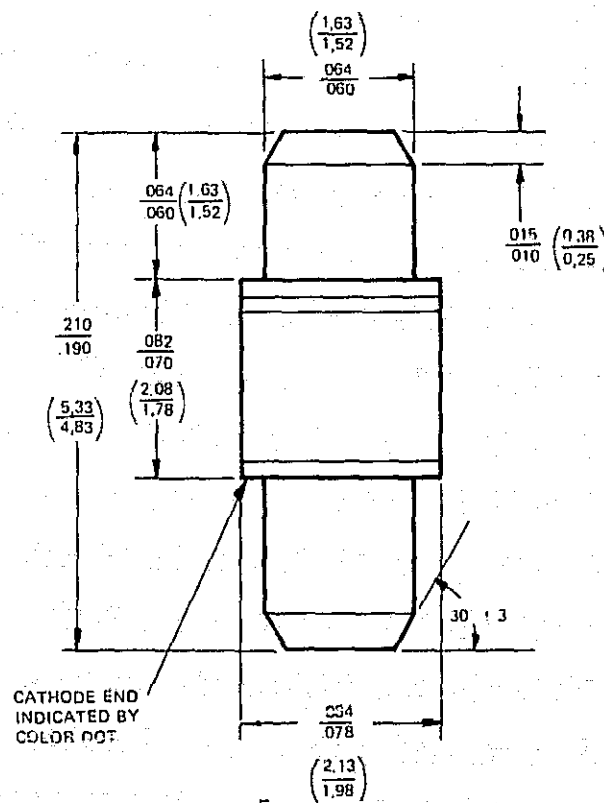


The data procedure for this experiment set-up is as follows:

1. Turn on all necessary power supplies while keeping the noise tube off. Note, it is necessary for sufficient gain to be present so that a convenient reference value can be located on the power meter. Record the power meter reading, P_1 . In addition, record the attenuator setting, A_1 .
2. Turn on the excess noise source. Check to see the duty cycle for the discharge tube is 50%.
3. With the noise source on, the power meter should indicate a higher power level. If not, additional gain is needed. Record this power meter value, this is P_2 , now slowly increase the rotary vane attenuator to bring the power meter level, P_2 , back to the initial setting, P_1 . Record the attenuator value, A_2 . Note that $A_2 > A_1$. The condition now exists where $P_2 = 2 P_1$. The difference between these two attenuator settings is the noise figure of the device.

TEST PROCEDURE

The two diodes tested were Hewlett-Packard's model 5082-2723 Silicon Schottky-Barrier diode and Alpha Industries, Inc. Model DMK-6602A Gallium-Arsenide Diode. Both diodes were supplied in double stud ceramic packages as shown below.

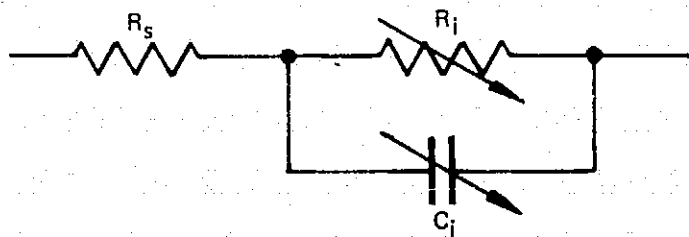


Supplied with both diodes were the manufacturer's specifications pertaining to noise figure, cut-off frequency, junction capacitance, junction resistance and series resistance. Shown below are the company's typical specified values.

Parameter	Hewlett Packard	Alpha Industries	Units
Noise Figure NF	6.3	5.3	dB
Cut-off Frequency f_{co}	136*	700	GHz
Junction Capacitance C_j	0.13	0.10	pf
Junction Resistance R_j	300 [†]	300 [†]	ohms
Series Resistance R_s	9	2.3*	ohms
*Calculate value [†] Typical value			1st I.F. noise figure = 1.8 dB

The first IF amplifier's noise figure is given above to rule out any error introduced by it. The IF amplifier's input was modified by introducing a series choke and resistor to ground thereby supplying a path for diode current.

The diode's equivalent circuit is shown below and will be used to identify the parameters set forth in the previous table.



The sensitivity of a low level detector is determined by various methods including the current responsivity (β), noise equivalent power (NEP) and tangential sensitivity (TSS).

The low level current responsivity, β , is defined as

$$\beta = \frac{8}{2nKT} \frac{1}{\left[1 + \frac{R_s}{R_j}\right] \left[1 + \left(\frac{f}{f_{co}}\right)^2\right]}$$

Where Q is the charge on an electron, 1.602×10^{-19} coulomb

n is the electron density ideality factor, 1.05 for hot carrier diodes.

K is Boltzmann's constant, 1.38×10^{-23} joules per $^{\circ}\text{K}$.

T is the temperature in Kelvin

R_s is the diodes series resistance

R_j is the diodes junction resistance

f is the operating frequency

f_{co} is the diodes cut-off frequency.

Therefore,

$$\beta = 1.906 \times 10^1 \left[\frac{1}{\left(1 + \frac{R_s}{R_j}\right) \left(1 + \left[\frac{f}{f_{co}}\right]^2\right)} \right]$$

and for silicon

$$\beta_{Si} = 1.83 \times 10^1 = 18.3$$

and for gallium-arsenide

$$\beta_{Ga As} = 1.89 \times 10^1 = 18.9$$

Noise equivalent power (NEP) is the term associated with the microwave input power required for a unity signal-to-noise ratio in a 1 Hz bandwidth at the output of the detector. This definition will be used to obtain a measure of the threshold sensitivity characteristic of both the silicon and gallium-arsenide diodes.

Noise equivalent power is calculated as

$$NEP = \frac{2nKT}{8} \left[\frac{4KTt\omega}{R_j} \right]^{1/2} \left[1 + \frac{R_s}{R_j} \right]^{1/2} \left[1 + \left(\frac{f}{f_{co}} \right)^2 \right] \left[1 + \frac{f_N}{f_{IF}} \right]^{1/2}$$

where $t\omega$ is the "white noise" temperature ratio, approximately 0.95

f_N is the noise corner frequency for the diode, 100 kHz for both silicon and Gallium-Arsenide

f_{IF} is the intermediate frequency, 300 MHz.

Thus,

$$NEP = 3.74 \times 10^{-13} \left[1 + \frac{R_s}{R_j} \right]^{1/2} \left[1 + \left(\frac{f}{f_{co}} \right)^2 \right] \left[1 + \frac{f_N}{f_{IF}} \right]^{1/2}$$

and for silicon

$$NEP_{Si} = 3.83 \times 10^{-13}$$

or

$$NEP_{Si} \text{ (dBm)} = -94.16 \text{ dBm}$$

and for gallium-arsenide

$$NEP_{GaAs} = 3.76 \times 10^{-13}$$

or

$$NEP_{GaAs} \text{ (dBm)} = -94.24 \text{ dBm.}$$

The tangential sensitivity, TSS, can be found by two methods. First, by adjusting the input power level to a level such that the highest noise peak, in the absence of the signal is at the same level as the lowest peak in the presence of the signal. This input level is then the tangential sensitivity. The second method is by calculating it from the noise equivalent power. Thus,

$$TSS = 2.5 \text{ (NEP)}$$

where B is the IF bandwidth 200 MHz.

Therefore,

$$TSS \text{ dBm} = \text{NEP dBm} + 45.5 \text{ dB}$$

and for silicon

$$TSS_{Si} \text{ dBm} = -48.65 \text{ dBm}$$

and for gallium-arsenide

$$TSS_{GaAs} \text{ dBm} = -48.73 \text{ dBm}.$$

Since a low level detector operates in the diode's square law region, the output voltage is proportional to the RF input power, the tangential sensitivity value is numerically proportional to the square root of the IF bandwidth.

By calculating the voltage sensitivity, an indication of the responsivity to a small signal is obtained. Since the voltage sensitivity, γ , is defined as $(R_j + R_s)\beta$, we find that for silicon

$$\gamma_{Si} = 5.65 \text{ mv/w}$$

and for gallium-arsenide

$$\gamma_{GaAs} = 5.7 \text{ mv/w}$$

The diode's loss needs to be examined too since it is a function of the junction capacitance and series resistance. By defining this loss as

where $\omega = 2\pi f$, we obtain for silicon

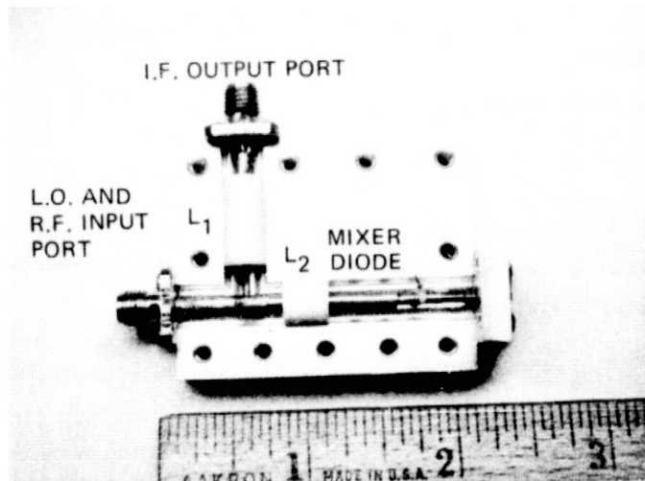
$$\zeta_{Si} \text{ dB} = 1.39 \text{ dB}$$

and for gallium-arsenide

$$\zeta_{GaAs} \text{ dB} = 0.25 \text{ dB}$$

It can be seen from the above that a small difference in the diode's series resistance and junction capacitance does effect its characteristic losses.

Below is a photograph of the diode housing used in both tests. This particular configuration, used in the down mixer of the 13.9 GHz radar, utilizes image enhancement to optimize the noise figure. The two diodes were introduced in the mount without any variation in the tuning loads L_1 and L_2 . Peak tuning was accomplished by an externally mounted stud.



It was found that in both cases the overall mixer frequency response from 200 MHz to 400 MHz, did not vary. Examination of the test data below indicates that the prime parameter change in the mixer was the local oscillator drive. The gallium-arsenide diode required about 8 dB more drive to achieve an IF power level similar to that obtained from the silicon diode.

SUMMARY

The noise figure test procedure described previously, gave the values shown below. Noise figure values for the silicon and gallium-arsenide diodes were 7.3 dB and 6.5 dB respectively. Because an oscilloscope/power meter arrangement was used, a sequence of runs were made in order to obtain a representative average value. In this averaging the highest and lowest values have been discarded.

It should be noted that for the noise figure tests run on the silicon and gallium-arsenide mixer diodes, the LO power level was selected to optimize the particular diodes NF response. In obtaining this optimal value, a low level 13.9 GHz CW signal was provided. A continuously variable 13.6 GHz LO drive allowed optimization as the IF output power was monitored and recorded for indications of crystal saturation. These values are shown in Figure 1.

The diode's mixer performance factors can be seen from the table of calculated and specified values shown below. Obviously the manufacturer's quoted noise figure is of importance, nevertheless, the performance (sensitivity) of each diode dictates its versatility in mixer design. Because the diode's cut-off frequency is inversely proportional to the junction capacitance and series resistance, any variation in these parameters is reflected in this cut-off frequency. Diode losses are also associated with these parameters, by their product squared. This is evident in the 1.14 dB difference in the loss experienced by the input signal power delivered to the junction resistance (R_j).

Bemus, Kuno and Candell, (Reference 1) have verified that in order to keep degradation of the optimum conversion loss less than 1 dB, it is required that $f_{co}/f_{sig} > 10$ and $R_{IF}/R_s > 10$. The gallium-arsenide diode satisfied both of these conditions. The silicon diode, however, is borderline, thus resulting in a higher loss value. The experimental conversion loss values include the loss introduced by less than ideal matches throughout the system.

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